Theor Appl Climatol (2017) 130:571–581
DOI 10.1007/s00704-016-1916-5

ORIGINAL PAPER

Variability and trends in daily precipitation extremes on the northern and southern slopes of the central Himalaya

Madan Sigdel[1,2,3] · Yaoming Ma[1,2,4]

Received: 31 October 2015 / Accepted: 18 August 2016 / Published online: 26 August 2016

Abstract This study focuses on the precipitation extremes recorded on the northern and southern slopes of the central Himalaya, especially those documented at higher altitudes. Daily precipitation data recorded over a 35-year period at nine meteorological stations in the region were studied. We used the precipitation extreme indices delineated by the Expert Team on Climate Change Detection and Indices (ETCCDI). The spatial and temporal variations in these precipitation extremes were calculated. When regional patterns were investigated to detect any anomalies, only 1 of the 10 precipitation extreme indices from the southern slopes of the central Himalaya showed a statistically significant trend; none from the northern slopes of the central Himalaya highlighted a statistically significant trend. On the southern slopes, all indices increased, apart from the maximum 1-day precipitation (RX1) and simple daily precipitation intensity (SDII) indices. Indices such as the consecutive dry days (CDDs) and RX1 indices exhibited similar increases on both the northern and southern slopes of the central Himalaya. These results suggest that increases in precipitation have been accompanied by an increasing frequency of extremes over the southern central Himalaya. Nonetheless, no relation could be established between the precipitation extreme indices and circulation indices for higher altitudes.

Keywords Precipitation · Trends · Extreme · Himalaya

✉ Madan Sigdel
sigdelbro@gmail.com

[1] Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China

[2] CAS Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing 100101, China

[3] Central Department of Hydrology and Meteorology, Tribhuvan University, Kathmandu, Nepal

[4] University of Chinese Academy of Sciences, Beijing 100049, China

1 Introduction

Much attention has been paid over recent years to a perceived increase in the frequency of extreme meteorological events. Many of these events have had a significant impact upon human society and infrastructure, and there is therefore an urgent need to document and understand such instances. This is certainly true of the periphery of the Himalaya, known as the "Third Pole" (Qiu 2008). This region has the largest concentration of glaciers outside the polar caps that is also, quite aptly, called the "Water Tower of Asia," as it provides ~8.6×10^6 m^3 of water annually (Dyurgerov et al. 1997) to its surrounding regions and countries. Any changes in the hydrological cycle are therefore going to have a significant impact upon the populations of these regions. Any study of climatic variability in high, mountainous terrain always provides challenges, not least in terms of the smaller number of meteorological stations located in such areas and consequently fewer datasets. However, there has recently been more of a focus on climate change in mountainous areas such as those found in Tibet and its surrounding regions, especially as the region shows evidence of being seriously affected by global warming (Chen et al. 2003; Duan et al. 2006). The Himalaya themselves are clearly highly sensitive to climate change and variability.

Many global studies relevant to changes in precipitation and temperature extremes have already been conducted (e.g., Alexander et al. 2006; Griffiths et al. 2005; Klein Tank et al. 2006; Moberg et al. 2006; Vincent et al. 2011; Wang et al.

2013; Donat et al. 2013; De Lima et al. 2015). Such studies have generally identified a trend toward more heavy precipitation extremes at the global scale, but with large regional differences.

Trends in climatic extremes during the twentieth century have been reported for countries neighboring the Himalaya, e.g., China (Zhai et al. 1999) and India (Roy and Balling 2004). The linear rates of temperature increase in the Mt. Everest region (1971–2004) exceeded the averages for China, and indeed the globe, for the same period (Yang et al. 2006). Some studies of climatic extremes have concentrated upon the northern slopes of the central Himalaya in Tibet (You et al. 2008; Song et al. 2011), but no direct correlation between changes in precipitation and temperature on the Tibetan Plateau (TP) has been established. These studies have not focused in particular upon the northern slopes of the central Himalaya. Baidya et al. (2008) studied daily climatic extremes over Nepal from 1971 to 2006, focusing their study on the lower altitude foothills of the Himalaya; they concluded that there were likely to be more frequent precipitation-related extreme events in the future.

There remains little research into precipitation regimes over the central Himalaya and none for higher altitudes. Additionally, the differences in climatic variability between the northern and southern slopes of the central Himalaya have yet to be fully explored; without such work, the exact sensitivity of the Himalayan region to climate change cannot be properly delineated. In this study, we focused on the higher altitudes of the Himalaya and investigated trends in daily precipitation extremes along the northern and southern slopes of the central Himalaya. In particular, we concentrated upon the variability and changes in the intensity, frequency, and duration of climatic extremes.

2 Study area and data

The Himalaya is the youngest and highest mountain range. They are bordered by the Karakoram and Hindu Kush ranges to the northwest, by the TP to the north, and by the Indo-Gangetic Plain to the south. Our study concentrated upon the central Himalaya, i.e., those mountains found in Nepal and adjacent areas of Tibet. Nine meteorological stations with relatively lengthy chronological records, i.e., six on the southern slopes of the central Himalaya (Nepal) and three on the northern slopes (Tibet), were used for data collection. All stations are higher than 2000 m above sea level (asl; Table 1; Fig. 1.).

Daily observed precipitation data from January 1975 to December 2009 was used in this study as the long-term dataset was difficult to get in this particular region. Data for stations on the southern slopes of the central Himalaya were provided by the Department of Hydrology and Meteorology of the Government of Nepal and for the northern slopes by the China Meteorological Administration (CMA). The study area itself is dominated by a wet monsoonal summer, but a cold, dry winter. Moreover, northern slopes are much dryer than the southern slopes.

3 Methods

The climate indices used in this study were first defined by the joint Commission for Climatology (CCl)/Climate Variability and Predictability (CLIVAR)/joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM) Expert Team (ET) on Climate Change Detection and Indices (ETCCDI) (Peterson et al. 2001) and reviewed by Zhang et al. (2011). A total of 10 precipitation extreme indices calculated using daily data were selected to explore changes in the intensity, frequency, and proportion of extreme precipitation events as a proportion of the total. The description of the selected indices is given in Table 2.

Before calculating the indices, RClimDex was used for the quality control of daily climatological data. Homogeneity was assessed using RH test software. The software and documentation are available on the ETCCDI website at http://www.etccdi.pacificclimate.org. Precipitation data were plotted for visual checks and the detection of outliers to avoid potential problems that may have caused changes in the seasonal cycle or variance in the data. The software highlighted any possible errors in the precipitation data, such as negative precipitation, allowing these invalid results to be isolated, removed, and recorded as missing data. Precipitation values above 200 mm were checked to ensure that their adjacent values were not set to missing, i.e., to make sure that high precipitation values were not due to accumulation over several days (Aguilar et al. 2005).

The indices were calculated on an annual scale for each individual station and also for the study region as a whole. The regional indices were assessed as simple averages of all stations' individual indices (i.e., to give all the stations equal weight) and were used to obtain an insight into the interannual variability of precipitation in the northern and southern slopes of the central Himalaya. The non-parametric Mann–Kendall test (Mann 1945; Kendall 1955) and Sen's slope estimates (Sen 1968) were used to calculate trends in the time series of precipitation extremes. Excel template application MAKESENS (FMI 2002) was applied for trend analysis, and statistical significance above a 95 % confidence interval was considered. Trends were calculated for the period 1975–2009.

Table 1 General information on meteorological stations, with annual total precipitation

SN	Station	Latitude (N)	Longitude (E)	Altitude (m asl)	Location	Annual total precipitation (mm)
1	Kakani	27 48	85 15	2064	SH	2348
2	Jiri	27 38	86 14	2003	SH	2298
3	Salleri	27 30	86 35	2378	SH	1672
4	Chourikharka	27 42	86 43	2619	SH	2097
5	Aiselukharka	27 21	86 45	2143	SH	2234
6	Chepuwa	27 46	87 25	2590	SH	2634
7	Niealer	28 11	85 58	3810	NH	547
8	Dingri	28 38	87 05	4300	NH	283
9	Pali	27 44	89 05	4300	NH	410

SH southern Himalaya, *NH* northern Himalaya

4 Results

4.1 Precipitation totals and intensity

The spatial distribution of temporal trends and regional annual anomalies in the precipitation indices are shown in Figs. 2, 3, and 4. A 4-year running mean was applied to the time series to highlight the long-term temporal patterns. Regional trends in precipitation indices are presented in Table 3.

The average regional series over the southern slopes of the central Himalaya indicated an increase in the annual total wet-day precipitation amount (PRCPTOT) of 41 mm *per* decade between 1975 and 2009. The lower and upper limits of the 95 % confidence interval were −20 and 101, respectively. The time series shown in Fig. 3a indicated that the years 1982 and 2006 had the lowest anomalies in PRCPTOT, while the years 1995 and 2003 had the highest. The decadal rising pattern over the decadal period 1994–2003 was observed using a 4-year running mean. The spatial patterns at most stations showed increasing trends, ranging from −40 to 180 mm per decade. One station (Jiri) reported an increasing trend with a statistically significant value at the 5 % level.

Conversely, regional patterns over the northern slopes of the central Himalaya showed decreases in the PRCPTOT of −3.7 mm per decade. The lower and upper limits of the 95 % confidence interval were −6.6 and 8.5, respectively. Figure 4a shows that the years 1976 and 1993 had the lowest anomalies and 1988 and 1989 the highest. Running mean time series identified a decadal rising pattern from 1980 to 1990. Individual stations indicated positive or negative trends across the region, but overall, the trend was not statistically significant (Fig. 2a).

The annual precipitation intensity (SDII) over the southern slopes of the central Himalaya showed little change, with a statistically insignificant regional trend of −0.13 mm per decade. The lower and upper limits of the 95 % confidence

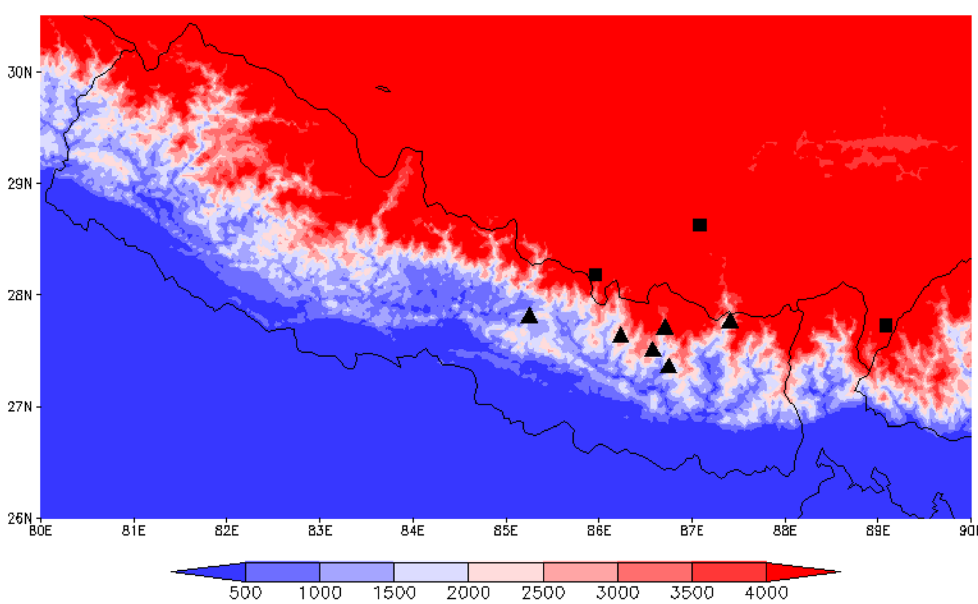

Fig. 1 Selected stations from the northern slopes of the central Himalaya (*solid squares*) and the southern slopes of the central Himalaya (*solid triangles*), with *shading* indicating altitude (m asl). For the names of the meteorological stations, please refer to Table 1

Table 2 Precipitation indices (base period 1975–2009)

Index	Description	Definition
CDD (days)	Consecutive dry days	Maximum length of dry spell (daily precipitation <1 mm)
CWD (days)	Consecutive wet days	Maximum length of wet spell (daily precipitation ≥1 mm)
PRCPTOT (mm)	Annual total wet-day precipitation	Annual total precipitation from days with precipitation ≥1 mm
R10 (days)	Heavy precipitation days	Number of days *per* year with daily precipitation ≥10 mm
R20 (days)	Very heavy precipitation days	Number of days *per* year with daily precipitation ≥20 mm
Rnn (days)	Extremely heavy precipitation days	Number of days *per* year with daily precipitation ≥threshold value (25 mm)
R95p (mm)	Precipitation on very wet days	Annual total precipitation >95th percentile
RX1 (mm)	Highest precipitation amount in 1-day period	Annual maximum precipitation over 1-day intervals
RX5 (mm)	Highest precipitation amount in five consecutive days	Annual maximum precipitation sums over 5-day intervals
SDII (mm)	Simple daily intensity index	Annual total precipitation divided by number of wet days (≥1 mm)

intervals can be observed in Table 3. The years 1982 and 2006 had the lowest anomalies, while 1985 and 1995 had the highest. Individual stations indicated positive or negative trends across the region. One station (Jiri) had a statistically significant positive trend, and two stations (Chepuwa and Aiselukhaka) reported statistically significant negatives.

SDII over the northern slopes of the central Himalaya showed very little change in regional trends (0.04 mm per decade). The years 1982 and 1993 had the lowest anomalies, while 1989 and 2007 had the highest. Individual stations showed very little change, and any change was statistically insignificant.

Consecutive dry days (CDDs) over the southern slopes of the central Himalaya increased by 4.2 days per decade, but the trend was not statistically significant. The years 1978 and 1996 had the lowest CDD anomalies, while 1997 and 2006 had the highest (Fig. 3c). Most of the stations showed a positive trend over the region, but only one station (Chourikharka) evinced a statistically significant value. Due to the predominance of the region's monsoonal climate, the

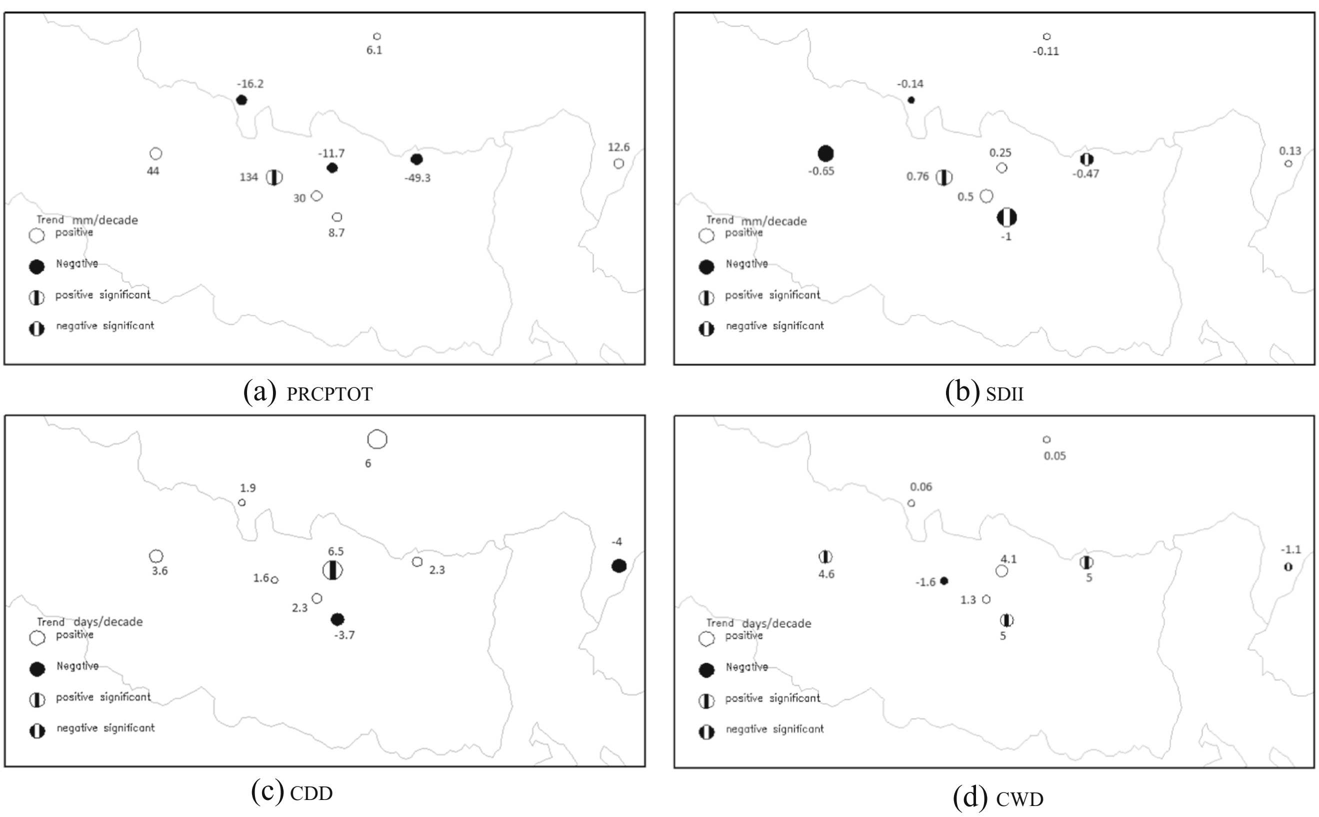

Fig. 2 Spatial trends in precipitation indices. The size (diameter) of the dot is proportional to the magnitude of the trend. **a** PRCPTOT, **b** SDII, **c** CDD, and **d** CWD

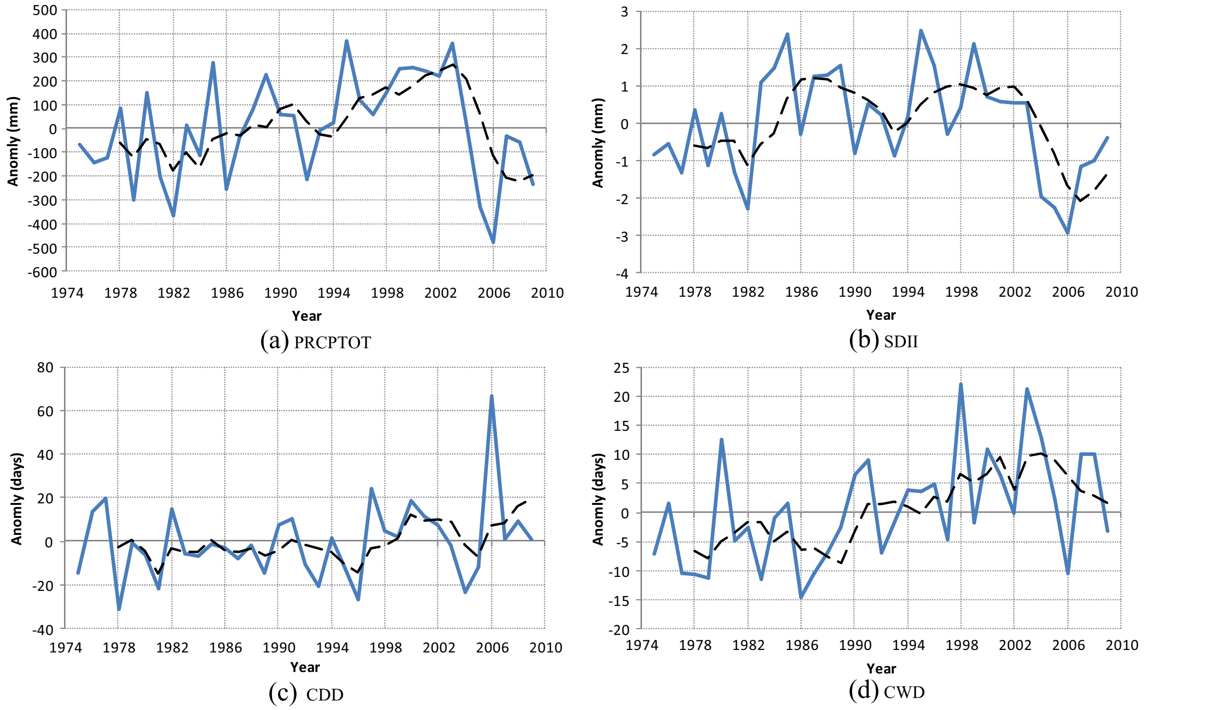

Fig. 3 Regional precipitation indices for the southern slopes of the central Himalaya. The *dashed black line* is the 4-year running mean; the *smoothed series* displays the trailing running average. North Himalaya (Tibet): **a** PRCPTOT, **b** SDII, **c** CDD, and **d** CWD

CDD index is mainly an indicator of the length of the dry season.

CDD values over the northern slopes of the central Himalaya showed a statistically insignificant positive trend of 0.9 days per decade. The years 1978 and 1989 had the lowest CDD anomalies, while the years 1985 and 2006 had the highest. Spatial patterns in trends ranged from −4 to 19 days per decade.

Consecutive wet days (CWDs) over the southern slopes of the central Himalaya showed a statistically significant increase of 4.7 days per decade. The lower and upper limits of the 95 % confidence interval were 1.8 and 7.3, respectively. The years

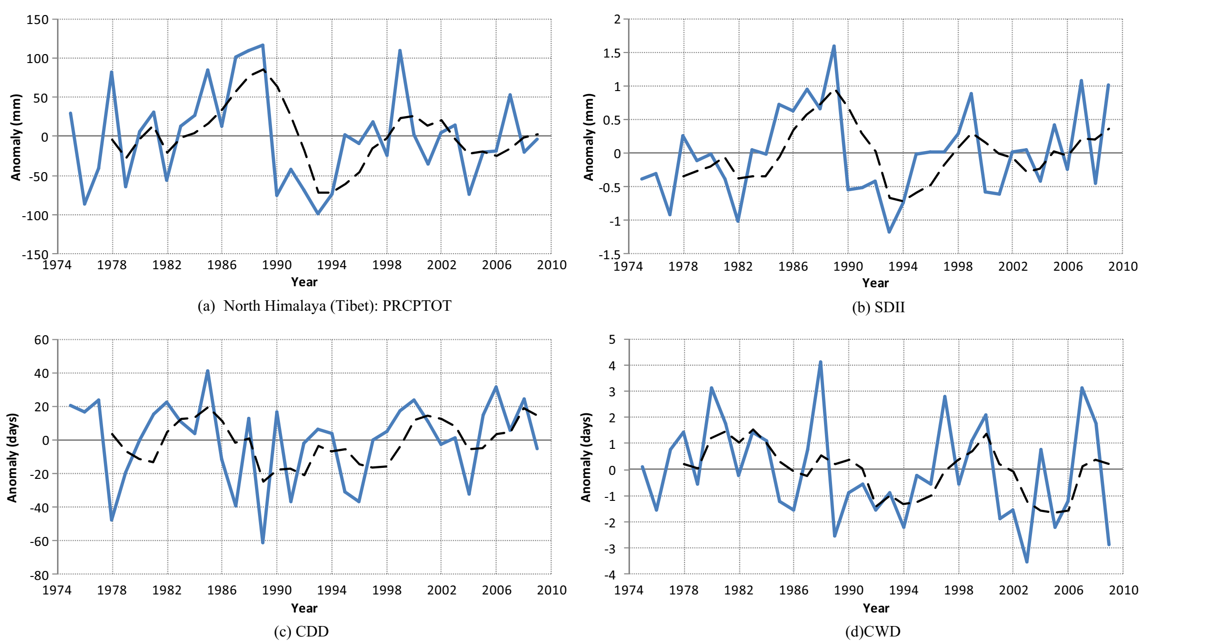

Fig. 4 Regional precipitation indices for the northern slopes of the central Himalaya. The *dashed black line* is the 4-year running mean; the *smoothed series* displays the trailing running average. **a** R10, **b** R20, **c** Rnn, **d** RX1, **e** RX5, and **f** R95p

Table 3 Trends per decade for southern and northern slopes of the central Himalaya, 1975–2009

Index	Unit	Southern Himalaya	Northern Himalaya
CDD	day	4.2 (−1.1 to 9.1)	0.9 (−6.6 to 8.5)
CWD	day	<u>4.7</u> (1.8 to 7.3)	−0.4 (−1.1 to 3.3)
PRCPTOT	mm	41 (−20 to 101)	−3.7 (−19.4 to 20.2)
R10	day	1.17 (−0.21 to 3.90)	−0.07 (−0.8 to 0.6)
R20	day	0.73 (−0.71 to 2.60)	−0.18 (−0.30 to 0.40)
Rnn	day	0.6 (−0.7 to 1.9)	−0.1 (−0.2 to 0.3)
R95p	mm	2 (−1.5 to 6.7)	−0.9 (−15.2 to16.2)
RX1	mm	−1.7 (−6.1 to 2.8)	−1.5 (−5.1 to 4.2)
RX5	mm	3.9 (−3.2 to 13.2)	−0.12 (−4.40 to 8.20)
SDII	mm/day	−0.13 (−0.72 to 0.44)	0.04 (−0.09 to 0.37)

Values statistically significant at 5 % are underlined. Parentheses are 95 % confidence intervals

1983 and 1986 had the lowest anomalies, while 1998 and 2003 had the highest. Half of the stations showed a statistical significant positive trend (i.e., Kakani, Chepuwa, and Aiselukharka; Fig. 2d).

The CWD index over the northern slopes of the central Himalaya showed a negative trend of −0.4 days per decade. The lower and upper limits of the 95 % confidence interval were −1.1 and 3.3, respectively. The years 2003 and 2009 had the lowest anomalies, while 1980, 1988, and 2007 had the highest. The spatial pattern of CWD over the northern slopes of the central Himalaya showed that two stations experienced a positive trend, while one station (Pali) had a statistical significant negative trend.

4.2 Precipitation extremes

The frequency of heavy (R10), very heavy (R20), and extremely heavy (Rnn) precipitation daily events recorded in the stations' data usually followed the respective regional average trends shown in Figs. 5, 6, and 7. These regional indices all showed a positive trend.

For R10, a statistically insignificant but positive trend of 1.17 days per decade was observed over the southern slopes of the central Himalaya; the lower and upper limits of the 95 % confidence interval were −0.21 and 3.90, respectively. The time series shown in Fig. 6a indicates the years 1979 and 2006 as having the lowest anomalies, while 1995 and 2002 had the highest. A sharp decadal-scale rise was observed for 1993–2002, as proven by the 4-year running mean. R10's spatial distribution indicates that two stations (Jiri and Aiselukharka) had positive trends with statistically significant values (Fig. 5a). For the R20 index, the years 1982 and 2006 had the lowest anomalies, while 1995 and 2001 had the highest. One station (Jiri) exhibited a statistically significant trend. The Rnn index experienced its lowest anomalies in 1982 and 2006 and its highest in 1985 and 1995. Its spatial trends and significance mirrored the R20 index.

R10, R20, and Rnn anomalies for the northern slopes of the central Himalaya all showed a statistically insignificant negative trend. The lower and upper limits of the 95 % confidence intervals are shown in Table 3. The R10 index experienced its lowest anomalies in 1993 and 2006 and its highest in 1988 and 1999 (Fig. 7a). The years 1992 and 2000 exhibited the lowest R20 anomalies and 1987 and 1989 the highest. Rnn anomalies were lowest in 1992 and 2000 and highest in 1985, 1987, and 1989. All spatial trends were insignificant.

The maximum 1-day precipitation index (RX1) for the southern slopes of the central Himalaya indicated a negative trend of −1.7 mm per decade. The years 2006 and 2009 had the lowest anomalies, while 1987 and 1995 had the highest. One station (Jiri) had a statistically significant positive trend and another (Aiselukharka) a statistically significant negative trend. The index for the maximum precipitation over five consecutive days (RX5) indicated a positive trend of 3.9 mm per decade. The years 1982 and 2006 had the lowest anomalies, while 1983 and 1996 showed the highest. Spatially one station (Jiri) had a statistically significant positive trend.

On the northern slopes of the central Himalaya, RX1 and RX5 overall exhibited insignificant negative trends. Regional RX1 values showed that 1992 and 2000 had the lowest anomalies and 1987 and 1989 the highest. For RX5, 1982 and 1990 exhibited the lowest anomalies and 1987 and 1989 the highest. All stations exhibited statistically insignificant trends.

The index for precipitation on very wet days (R95p) had a statistically insignificant positive trend of 2 mm per decade for the southern slopes of the central Himalaya. The lower and upper limits of the 95 % confidence interval were −1.5 and 6.7, respectively. The years 1976 and 1982 had the lowest anomalies, while 1985 and 1995 had the highest (Fig. 6d). Spatially, three stations showed a positive trend, while the other three stations indicated a negative trend. The stations at Jiri and Salleri exhibited a statistically significant positive trend.

On the northern slopes of the central Himalaya, the trend was also negative, at −0.9 mm per decade. The lower and upper limits of the 95 % confidence interval were −15.2 and 16.2, respectively. Regionally, the years 2000 and 2004 had the lowest anomalies, while 1985 and 1989 had the highest (Fig. 7d). Two stations exhibited a negative trend and one station a positive trend (Fig. 5f).

4.3 Correlation between precipitation indices

There were correlations between some of the indices across all the meteorological stations, but other indices

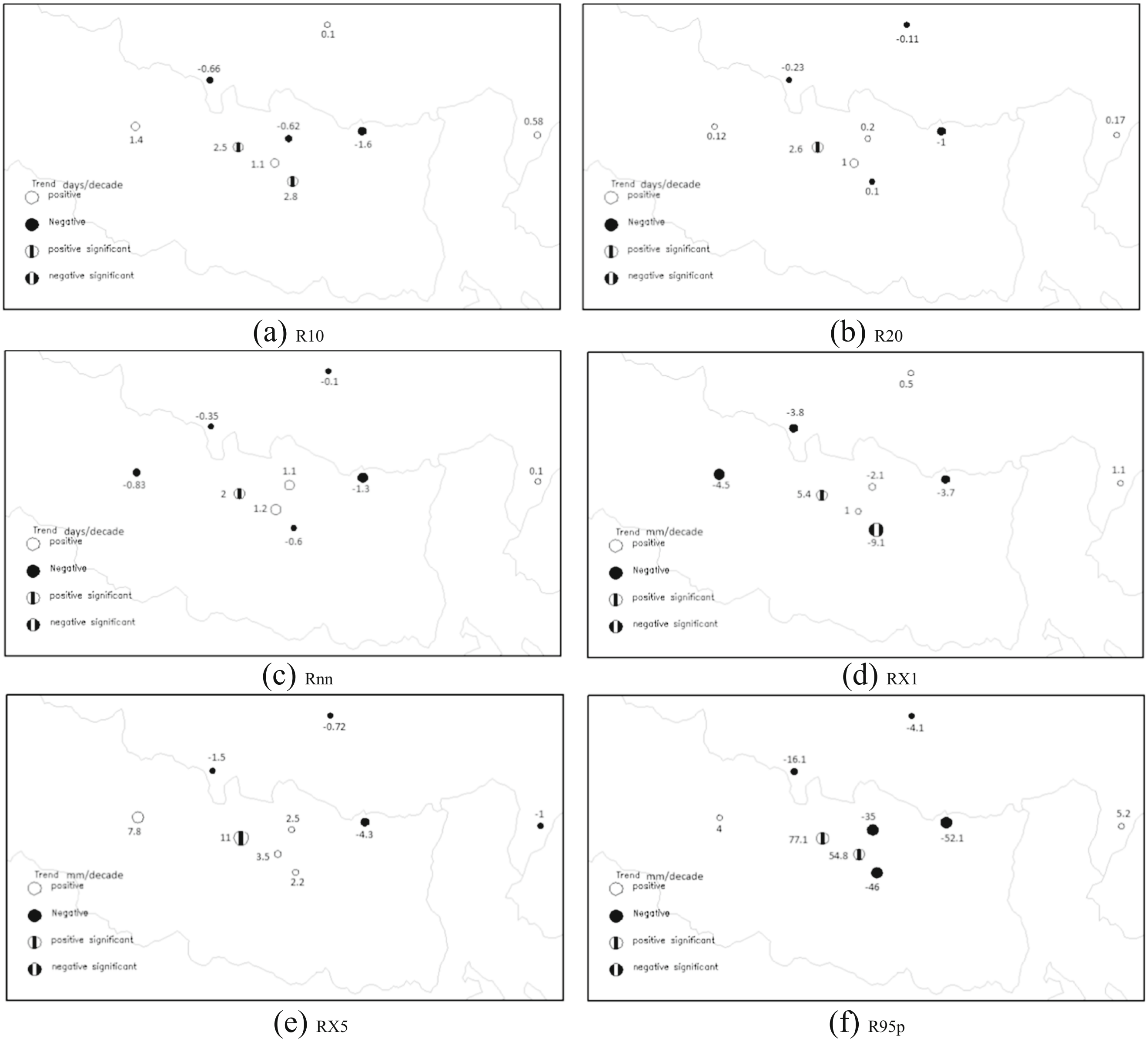

Fig. 5 Spatial trends in precipitation indices. The size (diameter) of the dot is proportional to the magnitude of the trend. **a** R10, **b** R20, **c** Rnn, **d** R95p, **e** RX1, and **f** RX5

evolved independently. Correlations, or otherwise, between the 10 precipitation indices are shown in Tables 4 and 5. We focused on six extreme precipitation indices and the PRCPTOT and SDII indices; the six extreme precipitation indices includes the three threshold indices (R10, R20, and Rnn), the two absolute indices (RX1 and RX5), and one percentile-based index (R95p).

The correlations between PRCPTOT and R10, R20, and Rnn were stronger ($r > 0.90$), while the average correlations between SDII and those same indices were 0.72. The correlation between R95p and SDII was stronger ($r > 0.75$) than with PRCPTOT ($r > 0.5$). Similarly, correlations between SDII with RX1 and RX5 ranged from $r > 0.6$–0.7, and the correlation between PRCPTOT and RX1 and RX5 ranged from $r > 0.64$–0.76.

Along the northern slopes of the central Himalaya, the average correlation between PRCPTOT and R10, R20, and Rnn was >0.7, more or less similar to that between SDII and these respective indices. The correlations between SDII and RX1/RX5 ($r > 0.7$–0.79) were higher than the correlations between PRCPTOT and RX1/RX5 ($r > 0.68$–0.78). The correlations between R95p and SDII/PRCPTOT were almost the same ($r > 0.8$). The correlations between PRCPTOT and SDII and the remaining indices were positive, apart from with CDD. Most of these correlations were statistically significant for both the southern and northern slopes of the central Himalaya.

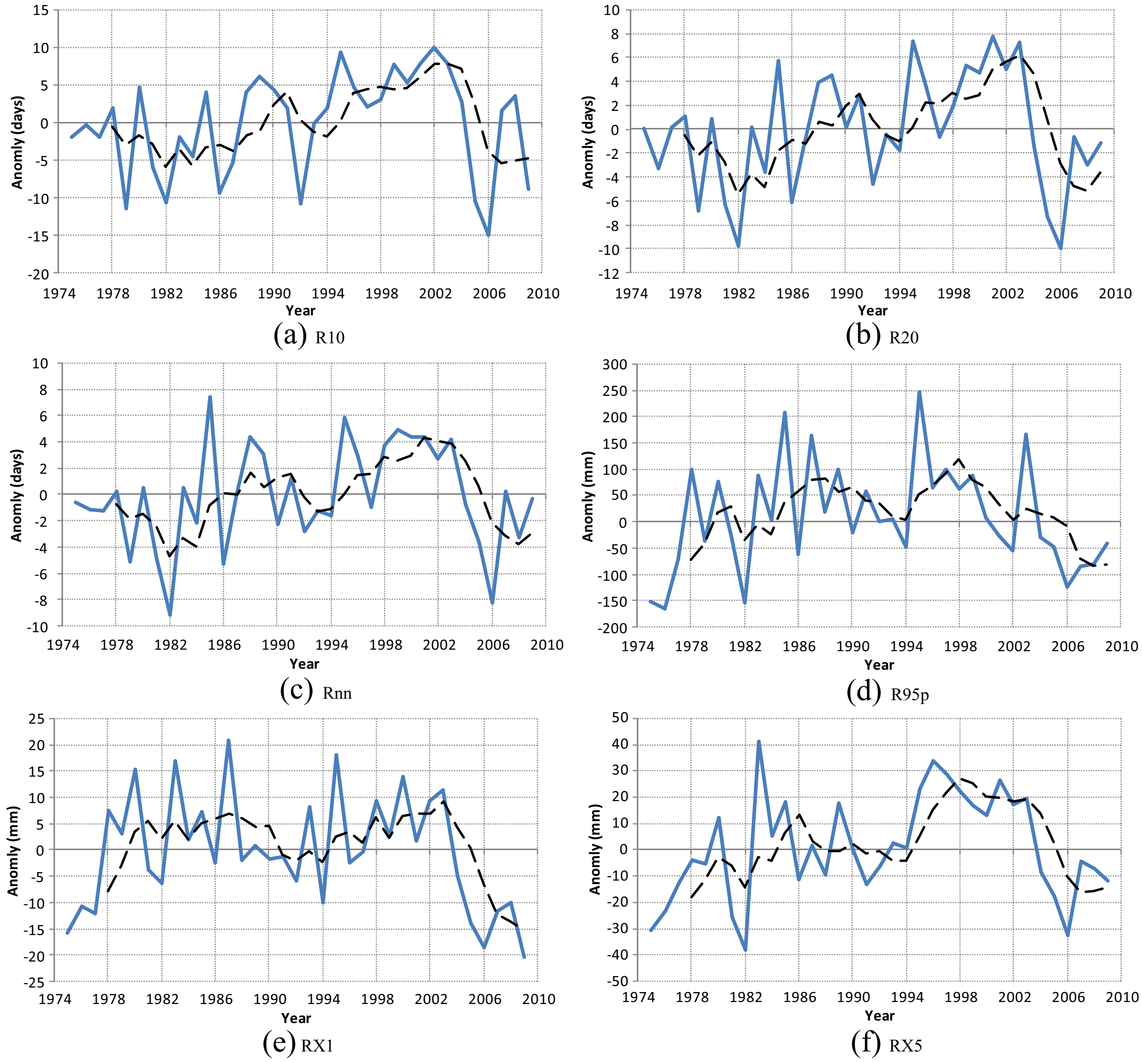

Fig. 6 Regional precipitation indices for the southern slopes of the central Himalaya. The *dashed black line* is the 4-year running mean; the *smoothed series* displays the trailing running average. **a** R10, **b** R20, **c** Rnn, **d** R95p, **e** RX1, and **f** RX5

5 Discussion and summary

Using the abovementioned indices for the period of 1975–2009, we observed changes in precipitation extremes on both the southern and northern slopes of the central Himalaya.

Over the southern slopes of the central Himalaya, there were some noticeable regional increases in the PRCPTOT index, indicating an increasingly wet climate, although this result was not statistically significant. Site-by-site analysis showed an incremental increase in the PRCPTOT index at 66 % of the stations over the southern slopes, with a statistically significant increase at one of them. The region-wide CDD index showed a statistically significant increase at 83 % of the stations. The regional CWD index showed an increase of 4.7 day per decade, which is statistically significant at the 95 % confidence level; >83 % of the stations exhibited increases, but only 50 % of them were statistically significant. Increasing trends were furthermore observed in regional R10, R20, and R25 indices, although overall these increases were not statistically significant. There was an increase in R95p values of 2 mm per decade. The RX1 index exhibited a negative trend of −1.7 mm per decade, while the RX5 index showed a positive trend of 3.9 mm per decade. Decreasing trends were observed for the regional SDII index. Correlation analyses suggested that precipitation extremes are closely correlated with mean annual total precipitation, particularly for the R10, R20, and R95p indices.

Most precipitation indices appeared to exhibit increasing trends over the southern slopes of the central Himalaya. The time series indicated that the year post 2003 decline seems to be sharper in the extreme indices than in the means. Both the CDD and CWD indices increased, but the increase in the CWD index was more noticeable. A strongly positive trend was reported for the PRCPTOT index and a positive trend for

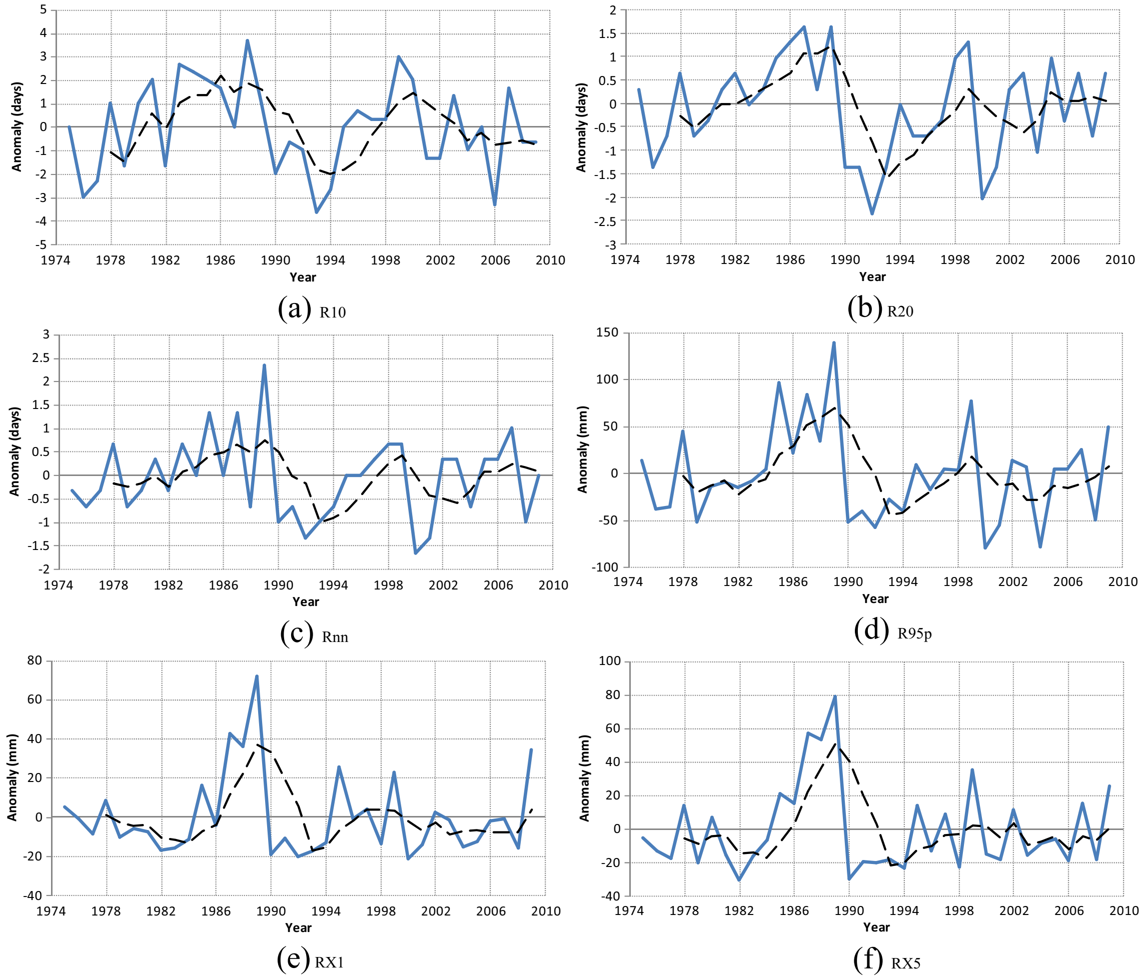

Fig. 7 Regional precipitation indices for the northern slopes of the central Himalaya. The *dashed black line* is the 4-year running mean; the *smoothed series* displays the trailing running average. **a** R10, **b** R20, **c** Rnn, **d** R95p, **e** RX1, and **f** RX5

the R95p index. This would suggest that increasing precipitation is accompanied by an increasing frequency in extreme events. The study conducted by Baidya et al. (2008) recorded increases in the R10, R20, R25, and PRCPTOT indices over the Himalayan foothills of Nepal. Our results from the southern slopes of the central Himalaya usually agree with these, indicating an increasing frequency in heavy and extreme precipitation events.

On the northern slopes of the central Himalaya, all indices (except for the CDD and SDII indices) exhibited negative

Table 4 Correlations between precipitation indices for the southern slopes of the central Himalaya

CDD		CWD	PRCPTOT	R10	R20	Rnn	R95P	RX1	RX5	SDII
CDD	1									
CWD	−0.02	1								
PRCPTOT	−0.25	0.51	1							
R10	−0.19	0.56	0.94	1						
R20	−0.20	0.41	0.95	0.89	1					
Rnn	−0.24	0.41	0.91	0.81	0.95	1				
R95P	−0.33	0.17	0.75	0.47	0.62	0.67	1			
RX1	−0.27	0.16	0.64	0.47	0.52	0.52	0.75	1		
RX5	−0.19	0.29	0.76	0.65	0.71	0.71	0.71	0.67	1	
SDII	−0.31	0.09	0.75	0.60	0.75	0.81	0.76	0.63	0.72	1

Table 5 Correlations between precipitation indices for the northern slopes of the central Himalaya

CDD		CWD	PRCPTOT	R10	R20	Rnn	R95p	RX1	RX5	SDII
CDD	1									
CWD	0.02	1								
PRCPTOT	−0.19	0.38	1							
R10	−0.04	0.43	0.8	1						
R20	−0.13	0.07	0.72	0.55	1					
Rnn	−0.18	0.02	0.69	0.47	0.82	1				
R95p	−0.17	−0.02	0.82	0.5	0.8	0.87	1			
RX1	−0.39	−0.02	0.68	0.29	0.51	0.6	0.82	1		
RX5	−0.37	0.18	0.78	0.44	0.58	0.62	0.82	0.91	1	
SDII	−0.25	0.10	0.8	0.65	0.75	0.79	0.83	0.7	0.79	1

trends, but these trends were weaker than for the southern slopes. None of the regional indices showed a statistically significant trend. The regional trend in PRCPTOT and R95p indices indicated a negative trend, along with the R10 and R20 heavy precipitation indices. These results suggest that the northern slopes of the central Himalaya experienced decreasing annual precipitation, accompanied by a decreasing frequency in extreme events. These observations correlate with the findings that, over the northern slopes of the central Himalaya, the CDD index has increased (showing a positive trend) and the CWD index has decreased (showing a negative trend). The fact that changes in precipitation extremes appear to be less significant than changes in temperature extremes concurs with the findings of Klein Tank et al. (2006).

Pandey et al. (2015) simulated future changes in climatic extremes by examining past precipitation extremes over the eastern Himalaya. They found that trends in precipitation-related indices lacked any consistent pattern. The stations Dingri and Pali in our study were also included in You et al. (2008) during the study for 1961–2005. The Pali station's trend of extreme indices presented in their study almost agreed with the results from this study too. However, their study stated that most precipitation indices for the southern TP have exhibited increases. This contrasts with our results from the northern slopes of the central Himalaya and may be due to limited and different topographical feature of the meteorological stations.

Using the HadEX2 dataset for the period 1951–2010, Donat et al. (2013) found that the R10 and R95p precipitation indices indicated a period of more intense precipitation over large swathes of Asia, implying a shorter dry spell over southern Asia, including the central Himalayan region. The northern slopes of the central Himalaya, including the southern TP, are comparatively dry. Moist air masses transported from the Bay of Bengal rise up the southern slopes of the Himalaya and fall as orographic rain (Yu et al. 2008). Annual total precipitation and precipitation intensity also therefore vary between the southern and northern slopes of the Himalaya, causing differences in precipitation extreme indices. Trends in precipitation extremes along the southern and northern slopes of the central Himalaya are therefore likely to be different and are also likely to contrast with other southern Asian regions.

The foothills of the Himalaya are sensitive to monsoonal circulations, as is the periphery of the central Himalaya to the El Niño–Southern Oscillation (ENSO) (Sigdel and Ikeda 2012). We analyzed the relations between annual precipitation extreme indices and the ENSO, the Indian Monsoon Index and the North Atlantic Oscillation Index, but any correlations appeared insignificant. Time series of total annual wet-day precipitation over southern Himalaya indicates that the years 1982 and 2006 were both El Niño years, but other strong El Niño years (e.g., 1997) do not show a strong reponse, suggesting that the relationship between ENSO and rainfall in this region is inconsistent. Although the Indian summer monsoon (ISM) contributes significantly to annual precipitation levels over Nepal and the central Himalaya, its influence decreases from the lower altitudes of the southern Himalaya to the higher altitudes of the northern TP. The vertical profiles for temperature, moisture content, and the velocity of the incoming air mass, which vary from storm to storm, as well as topographical factors such as the length, width, and height of the mountain range, determine how the atmosphere interacts with the mountains (e.g., Houze 1993). The Himalayas are a major topographic obstacle to the southwest monsoon, and hence, the northern slopes are much drier.

It should be noted that data availability for higher altitude rainfall networks is sparse, making data collection and analysis complex and problematic. However, it is clear that, as a general rule, precipitation extremes over the higher altitude slopes of the northern and southern regions of the central Himalaya exhibit differing spatial and temporal trends. The patterns and magnitudes inherent in these trends also appear to differ considerably from similar studies from other regions of the globe. Further research into the altitudinal/orographic impact on precipitation extremes at higher altitudes is therefore required, with a view to minimizing the risk of precipitation-induced disasters in the central Himalaya.

Acknowledgments We would like to thank the two anonymous reviewers for their constructive input. This research was funded by the National Natural Science Foundation of China (Grant Nos. 91337212 and 41275010), the CMA Special Fund for Scientific Research in the Public Interest (Grant No. GYHY201406001), and the External Cooperation Program of the Chinese Academy of Sciences (Grant No. GJHZ1207). The Chinese meteorological station data used in this study were provided by the Climate Data Center at the CMA National Meteorological Information Center.

References

Aguilar E, Peterson TC, Ramírez Obando P, Frutos R, Retana JA, Solera M, Soley J, González García I, Araujo RM, Rosa Santos A, Valle VE, Brunet M, Aguilar L, Álvarez L, Bautista M, Castañón C, Herrera L, Ruano E, Sinay JJ, Sánchez E, Hernández Oviedo GI, Obed F, Salgado JE, Vázquez JL, Baca M, Gutiérrez M, Centella C, Espinosa J, Martínez D, Olmedo B, Ojeda Espinoza CE, Núñez R, Haylock M, Benavides H, Mayorga R (2005) Changes in precipitation and temperature extremes in central America and northern South America, 1961–2003. J Geophys Res 110:D23107. doi:10.1029/2005JD006119

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Rupa Kumar K, Revadekar J, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res 111. doi:10.1029/2005JD006290

Baidya SK, Shrestha ML, Sheikh MM (2008) Trends in daily climatic extremes of temperature and precipitation in Nepal. J Hydrol Meterol 5:38–51

Chen B, Chao WC, Liu X (2003) Enhanced climatic warming in the Tibetan plateau due to doubling CO2: a model study. Clim Dyn 20:401–413. doi:10.1007/s00382-002-0282-4

De Lima MIP, Santo FE, Ramos AM, Tringo RM (2015) Trends and correlations in annual extreme precipitation indices for mainland Portugal, 1941–2007. Theor Appl Climatol 119:55–75. doi:10.1007/s00704-013-1079-6

Donat M, Alexander L, Yang H, Durre I, Vose R, Dunn R, Willett K, Aguilar E, Brunet M, Caesar J. (2013) Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: the HadEX2 dataset. J Geophys Res: Atmospheres

Duan A, Wu G, Zhang Q, Liu Y (2006) New proofs of the recent climate warming over the Tibetan plateau as a result of the increasing greenhouse gases emissions. Chin Sci Bull 51: 1396–1400. doi:10.1007/s11434-006-1396-6

Dyurgerov MB, Meier MF (1997) Year-to-year fluctuations of global mass balance of small glaciers and their contribution to sea-level changes. Arc Alp Res 29:392–401 http://www.jstor.org/stable/1551987

FMI (2002) Detecting trends of annual values of atmospheric pollutants by the Mann–Kendall test and Sen's slope estimates: the excel template application MAKESENS. Finnish Meteorological Institute, Finland

Houze RA (1993) Cloud dynamics. Academic Press, Boston, p. 573 p

Klein Tank AMG et al. (2006) Changes in daily temperature and precipitation extremes in central and South Asia. J Geophys Res 111(D16): 105. doi:10.1029/2005JD006316

Kendall MG (1955) Rank correlation methods. Hafner Publishing Co, New York, p. 196 pp http://www.jstor.org/stable/1907752

Mann HB (1945) Nonparametric tests against trend. Econometrica 13: 245–259 http://www.jstor.org/stable/1907187

Moberg A, Jones PD, Lister D, Walther A, et al. (2006) Indices for daily temperature and precipitation extremes in Europe analyzed for the period 1901–2000. J Geophys Res 111:D22106. doi:10.1029/2006JD007103

Peterson TC, Folland C, Gruza G, Hogg W, Mokssit A, Plummer N (2001) Report on the Activities of the Working Group on Climate Change Detection and Related Rapporteurs 1998–2001. World Meteorological Organization, WCDMP–No. 47/WMO–TD No.1071: Geneva, Switzerland

Panday PK, Thibeault J, Frey KE (2015) Changing temperature and precipitation extremes in the Hindu Kush-Himalayan region: an analysis of CMIP3 and CMIP5 simulations and projections. Int J Climatol 35:3058–3077

Qiu J (2008) The third pole. Nature 454(24):393–396

Roy SS, Balling JRC (2004) Trends in extreme daily precipitation indices in India. Int J Climatol 24:457–466

Sigdel M, Ikeda M (2012) Summer monsoon rainfall over Nepal related with large scale atmospheric circulations. J Earth Sci Climate Change 3(112). doi:10.4172/2157-7617.1000112

Song M, Ma Y, Zhang Y, Li M, Ma W, Sun F (2011) Climate change features along the Brahmaputra Valley in the past 26 years and possible causes. Clim Chang 106:649–660. doi:10.1007/s10584-010-9950-2

Sen PK (1968) Estimates of the regression coefficients based on Kendall's tau. J Am Stat Assoc 63:1379–1389 http://www.jstor.org/stable/2285891

Vincent LA, Aguilar E, Saindou M, Hassane AF, Jumaux G, Roy D, Booneeady P, Virasami R, Randriamarolaza LYA, Faniriantsoa FR, Amelie V, Seeward H, Montfraix B (2011) Observed trends in indices of daily and extreme temperature and precipitation for the countries of the western Indian Ocean, 1961–2008. J Geophys Res 116: D10108. doi:10.1029/2010JD015303

Wang H, Chen Y, Chen Z (2013) Spatial distribution and temporal trends of mean precipitation and extremes in the arid region, northwest of China, during 1960-2010. Hydrol Process 27:1807–1818. doi:10.1002/hyp.9339

Yang X et al. (2006) Climate change in Mt. Qomolangma region since 1971. J Geogr Sci 16:326–336. doi:10.1007/s11442-006-0308-7

You Q, Kang S, Aguilar E, Yan Y (2008) Changes in daily extremes in the eastern and central Tibetan plateau during 1961-2005. J Geophys Res 113:D07101. doi:10.1029/2007JD009389

Yu W, Yao T, Tian L, Ma Y, Ichiyanagi K, Wang Y, Sun W (2008) Relationship between ∂18O in precipitation and air temperature and moisture origin on a south north transect of the Tibetan plateau. Atmos Res 87(2):158–169

Zhai P, Sun A, Ren F, Liu X, Gao B, Zhang Q (1999) Changes of climate extremes in China. Clim Chang 42:203–218

Zhang X, Alexander L, Hegerl C, Jones P, Klein Tank A, Peterson C, Trewin B, Zwiers Francis W (2011) Indices for monitoring changes in extremes based on daily temperature and precipitation data. WIREs. Clim Chang 2:851–870. doi:10.1002/wcc.147